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Dynamic groundwater-pit lake coupling for a multi-pit closure application in a structurally complex aquifer: a case study

Luisa Ventura [a,*], Giancarlo Lopes [a], Lorrayne Silva [a], Andrea Garcia-Forero [a]

[a] *WSP, Australia*

Abstract

Predicting long-term pit lake recovery is a key challenge in mine closure, particularly in multi-pit systems where groundwater recovery, pit lake filling, and hydraulic connectivity evolve. This paper presents a case study applying a dynamically coupled groundwater-pit lake water balance modelling framework to assess post-closure recovery of a complex multi-pit closure system in the Pilbara region of Western Australia. Two closure scenarios were assessed over a 300-year simulation period: a base case comprising ten persistent pit lakes and a backfill case comprising four remaining pit lakes following partial backfilling.

The modelling framework linked a three-dimensional transient FEFLOW groundwater model with a GoldSim water balance model through a Python-based interface, enabling bi-directional exchange of hydraulic information without modification of either model. The groundwater model was calibrated against ten years of groundwater level observations from 132 monitoring locations prior to implementation of the coupled framework. The approach was developed to represent the structurally complex hydrogeological setting, characterised by groundwater compartmentalisation and evolving pit-to-pit interactions.

The results indicated that the groundwater recovery rate was greatest during the first decades following closure and declined progressively as hydraulic gradients declined between the pits and surrounding aquifer. Groundwater levels approached quasi-equilibrium after approximately 50–100 years but remained below pre-mining levels in both scenarios. Evaporation remained the dominant long-term control on pit lake water balances, while pit lake behaviour evolved throughout the recovery period as hydraulic connectivity between pits changed. The backfill case generally produced higher long-term pit lake levels and smaller groundwater recovery deficits compared with the base case.

This case study evaluated groundwater recovery, pit lake water balances, and hydraulic connectivity during post-closure recovery. Computational demands limited the analysis to three deterministic realisations and therefore constrained the probabilistic assessment. The results illustrate how groundwater-pit lake interactions changed through time under the evaluated closure scenarios.

Keywords: *pit lake, model coupling, FEFLOW, GoldSim, groundwater-surface water interaction.*

1 Introduction

Predicting the long-term recovery of pit lakes following large-scale open cut mining is a key uncertainty in mine closure, particularly where pits extend below the groundwater table (McCullough et al. 2011). It is a technically demanding aspect of mine closure as it typically requires the integration of multiple modelling components to represent the surface water balance, groundwater interaction, and water quality evolution. Moreover, the inclusion of climate change analysis and its inherent variability underscore the need for probabilistic simulation to capture a wide range of potential future hydrological outcomes (Garcia-Forero et

[*] Corresponding author. Email address: luisa.ventura@wsp.com

al. 2023; Tomlin et al. 2025). This challenge is further amplified in geologically complex domains, where orebody deposits are hosted within folded, faulted, and compartmentalised stratigraphic sequences.

A range of modelling approaches can be used to assess pit lake systems, ranging from simple analytical methods to fully integrated numerical frameworks (Tomlin et al. 2025). For the purposes of this paper, the available literature is grouped into four broad categories: i) Simplified analytical approaches; ii) Loosely linked numerical models; iii) Single-platform embedded pit lake-aquifer simulation; iv) Dynamically coupled multi-platform models.

Tomlin et al. (2025) report that current practice commonly applies water balance models to simulate pit void water levels and solute mass balances, with groundwater seepage estimated using analytical equations or numerical groundwater flow models. Groundwater impact is typically undertaken using separate groundwater models that adopt water levels predicted by the water balance as inputs.

Simplified analytical approaches for estimating pit inflow and pit lake evolution include classical steady-state analytical equations and more recent analytical water-balance formulations. They are generally used for screening studies, early-stage closure assessments or conceptual understanding of pit filling and groundwater level recovery. These methods typically rely on idealised pit geometry, homogeneous aquifer assumptions, and simplified formulations of groundwater inflow and pit lake water level recovery (Dennis & Dennis 2016; Halford 2026; Jackson et al. 2026; Marinelli & Niccoli 2000).

The main advantages of the analytical approach are low data requirement, rapid implementation, computational efficiency, and transparency of assumptions, which make them particularly useful for first-pass assessment, sensitivity testing, and preliminary comparison of closure options (Halford 2026; Jackson et al. 2026; Marinelli & Niccoli 2000). However, these approaches generally rely on substantial simplifications of aquifer geometry, hydraulic gradients, and boundary conditions. As a result, their reliability is greater where the system behaviour is consistent with the adopted assumptions. Dennis & Dennis (2016) also reinforce that simplified analytical methods are most appropriate for single-pit or near-isolated systems.

Loosely linked numerical modelling approaches are commonly used in mine closure studies in which groundwater flow and pit lake or mine-void water balances are simulated using separate models (Dogramaci 2025; Garcia-Forero et al. 2023). One of the main advantages of this approach is the practical flexibility which allows groundwater flow, water balance, and water quality components to be developed, calibrated, and reviewed separately using tools well suited to each task (Castendyk et al. 2023; Dogramaci 2025; Turvey 2022). It can also accommodate varying levels of detail across model components and allow studies to proceed even where some parts of the system are data limited (Garcia-Forero et al. 2023).

While this structure allows specialised tools to be applied to each process, the models are not dynamically linked during runtime. As a result, changes in pit-lake stage do not feed back into the groundwater simulation, limiting the representation of coupled, transient interactions. Turvey (2022) demonstrates that loosely linked models can represent some degree of stage dependency and provide a practical bridge between numerical groundwater simulation and pit lake prediction. However, the interaction remains sequential rather than fully coupled.

A more integrated approach involves simulating pit lake-groundwater interaction within a single modelling platform. In these models, groundwater flow and pit lake water exchange are represented internally within the same numerical model (Langevin et al. 2017; Merritt & Konikow 2000). These approaches have since been widely applied to pit lake systems in mining and closure studies but remain constrained by the assumptions and capabilities of the host platform and lake package (Bozan et al. 2022; Carlino & McCullough 2019; Gresswell et al. 2019; Moser et al. 2024).

Single-platform embedded approaches represent an important step toward greater physical consistency. A key advantage of this approach is that lake stage and lake-aquifer exchange are solved within the same numerical framework, providing a stronger degree of hydraulic consistency than more loosely linked workflows. However, they do not necessarily provide the flexibility required for all closure problems, particularly those involving complex multi-pit feedback, advanced uncertainty analysis, or tightly integrated water quality and operational decision frameworks (Tomlin et al. 2025).

Tomlin et al. (2025) note that more complex processes, such as stratification and detailed geochemical behaviour, are rarely modelled at the approvals stage. Dynamically coupled groundwater-water balance models that exchange information at each timestep remain largely confined to a small number of theoretical published examples (Janzen et al. n.d; Martin & Gabora 2018).

The main advantage of dynamically coupling is that each modelling platform can be used for the process it represents best, while maintaining feedback between components during simulation. This makes dynamically coupled workflows particularly suitable where closure behaviour depends on 2-way interaction between groundwater flow and pit lake or system-scale water balance processes, rather than on externally prescribed fluxes or sequential updates (Martin & Gabora 2018). However, Martin & Gabora (2018) identify complexity, required technical skill, and FEFLOW stability challenges under extreme dynamic forcing as primary drawbacks. Janzen et al. (n.d.) also highlight the run time as one of the main limitations.

Building on this context, this paper presents a case study applying a dynamically coupled groundwater-water balance modelling framework to simulate the long-term recovery of a complex multi-pit closure system in the Pilbara region of Western Australia. The case comprises ten hydraulically interconnected pits hosted within a folded and faulted stratigraphic sequence and influenced by historical dewatering and climate variability.

The objective of this paper is to present this case study and its application of a dynamically coupled groundwater-water balance modelling framework to assess post-closure recovery in a complex multi-pit system. The paper describes the modelling methodology, presents the key findings, and discusses practical considerations associated with the application, including computational requirements, project constraints, and limitations of the probabilistic analysis.

2 Modelling approach selection

No single methodology of the four outlined is universally superior. Instead, each approach occupies a different position along the spectrum of conceptual complexity, data requirements, computational cost, and process representation.

At one end of the spectrum, analytical approaches are generally considered more applicable to early-stage screening and systems that can be reasonably approximated using homogeneous properties and simplified geometry (Halford 2026; Marinelli & Niccoli 2000). At the other end of the scale, dynamically coupled multi-platform models tend to be more suitable where groundwater inflow cannot be prescribed independently of lake evolution, such as in transient, structurally complex, hydraulically connected multi-pit systems (Martin & Gabora 2018).

Between these two extremes, loosely linked numerical models and single-platform embedded pit lake-aquifer simulation models offer intermediate levels of physical realism and practical applicability.

Loosely linked numerical models provides a practical and efficient way to integrate groundwater recovery predictions with site-specific water balance terms and closure assumptions in a form readily adaptable for scenario testing. At the same time, this type of workflow relies on the assumption that groundwater inflows generated by the groundwater model remain valid when transferred to the external pit lake balance, even though the evolving pit lake stage and salinity may not feed back into the groundwater simulation (Garcia-Forero et al. 2023).

Bozan et al. (2022), Carlino & McCullough (2019), Gresswell et al. (2019) and Moser et al. (2024) show that embedded lake packages can provide a practical and physically coherent means of simulating pit lake filling, hydraulic recovery, and groundwater exchange within a single solver. This approach is especially useful when model stability, mass balance consistency, and internal treatment of lake stage evolution are more important than external flexibility. However, embedded approaches remain constrained by the assumptions and capabilities of the host platform and lake package. These constraints include simplifications in lake representation, external flow, and limitations in managing multiple lakes or changing operational conditions.

Accordingly, methodology selection should be guided not only by model availability or workflow preference, but by whether the chosen model class can adequately represent the dominant processes controlling pit lake recovery. It is important to note that limited data or budget alone should not justify an overly simplified modelling approach where the hydrogeologic system is clearly complex. In such cases, a simplified model may still be useful for screening purposes, but its limitations should be clearly acknowledged, particularly if the results are intended to inform final closure decisions.

Table 1 summarises the conditions under which each modelling methodology may be more applicable based on a literature review. Key limitations and primary controls on methodological adequacy and practical constraints on implementation are also synthesised.

Table 1 Summary of applicability and limitations for the modelling approaches based on literature review

Criteria	Analytical approaches	Loosely linked	Single-platform embedded	Dynamically coupled
Typical use	Screening, no pit-to pit interaction, low data availability	External groundwater flux inputs	Hydraulically consistent simulation on one platform	Complex, feedback-dominated multi-pit closure systems
Main limitation	Oversimplifies heterogeneity and feedback	Runtime feedback	Package assumptions and less flexible	High development effort and higher run times
Hydrogeologic complexity	Low	Moderate	High	High
Pit lake/aquifer feedback	Prescribe/none	Sequential, between runs	Solved within one solver	Continuous, two-way at runtime
Inter-pit lake interaction	Not applicable	Weak/approximate	Resolved within solver	Strong, time-varying
Transient storage/delayed	Quasi-steady	Transient GW; lagged feedback	Represented in package	Fully resolved
Uncertainty/ Monte Carlo capability	Well suited	Well suited	Moderately suited (runtime)	Limited by runtime
Computational demand	Low	Low	Moderate to high	High to very high
Implementation complexity	Low	Moderate	Moderate	High

3 Case study description

3.1 Study overview

The case study comprises an open pit iron ore operation in the Pilbara region of Western Australia, where mine closure is expected to result in the formation of multiple pit lakes following cessation of mining and groundwater abstraction. To maintain project confidentiality, site-specific identifiers such as pit names and mine identifiers have been omitted. The case study description is limited to the hydrogeological characteristics required to explain the coupled modelling methodology.

The study assessed long-term post-closure recovery under alternative rehabilitation strategies over 300 years, including groundwater response, pit lake development, inter-pit hydraulic connectivity and potential effects on surrounding environmental receptors. Two closure configurations were evaluated, representing final pit geometries (base case), and partially backfilling pits (backfill case). Depending on the rehabilitation strategy, between four (backfill case) and ten (base case) pit lakes were predicted to persist following groundwater recovery. Based on the scenario geometry, the combined storage volume of the remaining pit lakes decreased from approximately 925 GL in the base case to 520 GL in the backfill case, representing a reduction of about 44%. Individual reductions in pit lake volumes ranged from approximately 19 to 69%. Pit floor elevations remained unchanged for the pits retained in both scenarios.

3.2 Hydrological and hydrogeological setting

The study area comprises two adjacent iron ore deposits containing multiple final voids with contrasting depths, geometries and hydraulic settings. Following closure, groundwater recovery is expected to occur at different rates across the site, producing a combination of terminal sink lakes, through-flow lakes and partially connected pit lake systems.

The hydrogeological setting is characteristic of Pilbara iron ore operations, where groundwater systems are controlled by low recharge, high evaporative demand and strong structural compartmentalisation. Mean annual rainfall is approximately 400 mm, whereas potential evaporation exceeds 3,000 mm/year. Consequently, evaporation represents the dominant long-term water loss mechanism controlling pit lake evolution.

Groundwater flow is strongly influenced by low-permeability dykes and non-aquifer units that compartmentalise the aquifer into partially connected hydraulic domains. As groundwater recovery progresses, evolving hydraulic gradients modify groundwater exchange between neighbouring pits, causing hydraulic connectivity to change continuously throughout the simulation period. Figure 1 presents the conceptual model for pre-mining and post-closure for the study area.

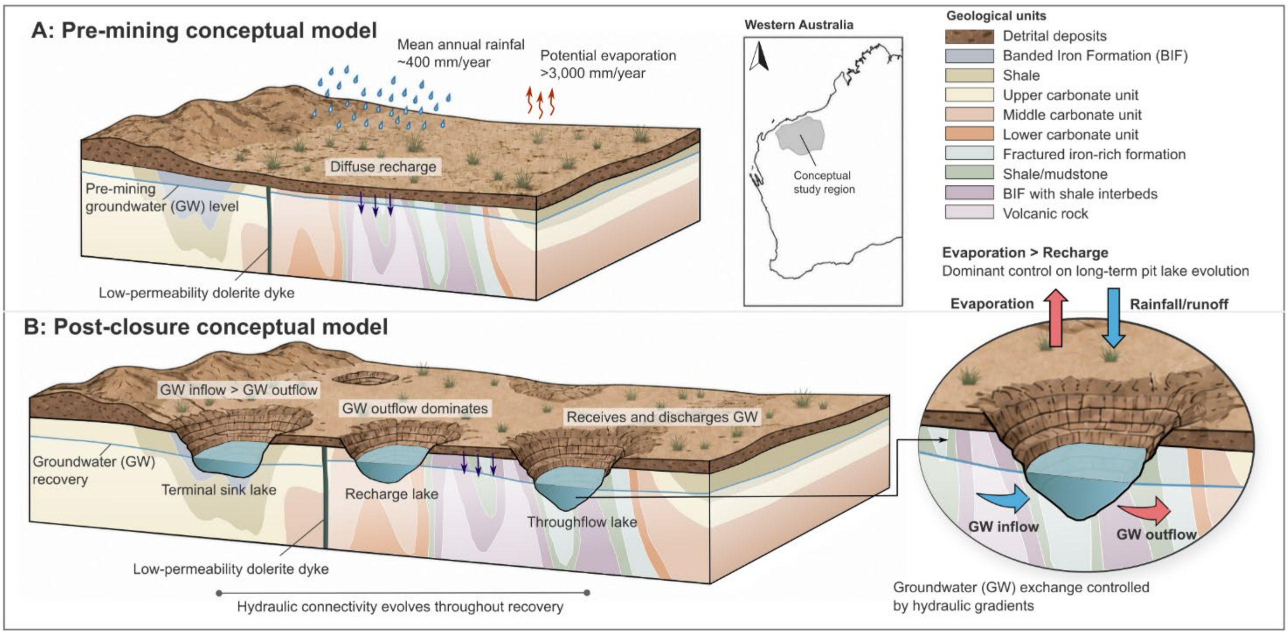

Figure 1 Conceptual model. (a) Pre-mining (Pilbara Craton Region); (b) Post-closure

3.3 Numerical models

Groundwater recovery was simulated using a three-dimensional transient FEFLOW v10.0 model covering approximately 900 km². The model comprises ten hydrostratigraphic layers discretised using an unstructured finite-element mesh and was calibrated independently under steady-state and transient conditions against observed groundwater levels.

Pit lake evolution was simulated using a GoldSim v15 water and solute balance model representing groundwater inflow, direct rainfall, runoff, groundwater outflow, and evaporation. Simulations were undertaken over a 300-year period using stochastic climate realisations to represent long-term climatic variability.

Although both models were developed independently, pit lake evolution depends on continuous feedback between groundwater flow and lake water balance. Groundwater inflows control lake filling, whereas changing lake levels modify hydraulic gradients and groundwater exchange between pit and adjacent aquifer. Representing this interaction required dynamic bi-directional coupling using a Python code throughout the predictive simulations.

3.4 Model calibration

The groundwater model was calibrated independently prior to implementation of the coupled modelling framework. Calibration was undertaken using a deterministic trial-and-error approach against groundwater level observations from 132 monitoring locations spanning approximately ten years. Both steady-state hydraulic heads and transient groundwater responses were used to constrain model parameters and evaluate model performance.

Hydraulic conductivity was calibrated using a zonal approach based on the defined hydrostratigraphic units, with parameter values remaining within conceptual ranges derived from previous investigations, pumping tests, and the site conceptual hydrogeological model. Hydraulic anisotropy was incorporated to represent preferential flow along the dominant geological strike direction. During transient calibration, specific yield, specific storage, recharge, and boundary conditions were refined to reproduce observed groundwater level trends, seasonal responses, and regional hydraulic stresses.

Calibration performance was assessed using groundwater modelling metrics recommended by the Australian Groundwater Modelling Guidelines (Barnett 2012). The steady-state calibration achieved a root mean square error (RMS) of 2.48 m and scaled RMS (SRMS) of 4.78%, while the transient calibration achieved a RMS of 3.61 m and SRMS of 3.90%.

Unlike the groundwater model, calibration of the GoldSim water balance model was not feasible because the simulations represent future post-closure conditions for a proposed mining development. No observed pit lake levels or recovery data were available for comparison.

4 Methodology for the coupled modelling framework

4.1 General coupled modelling framework

To represent the dynamic interaction between groundwater recovery and pit lake evolution, a coupling framework was developed to link the independently developed FEFLOW groundwater model with the GoldSim pit lake model. Rather than integrating both processes within a single numerical engine (i.e. single-platform embedded), the coupled modelling framework preserves the native formulation of each model while enabling bi-directional exchange of hydraulic information during model runtime.

During each synchronisation interval, GoldSim first updates the pit lake water balance using groundwater exchange fluxes calculated during the previous interval. The resulting pit lake water levels are transferred to FEFLOW and applied as hydraulic boundary conditions for the corresponding pit lakes and timestep. FEFLOW then advances the transient groundwater simulation and computes updated groundwater exchange fluxes, which are returned to GoldSim for the subsequent water balance calculation. This sequential exchange is repeated throughout the simulation, allowing groundwater recovery and pit lake evolution to evolve as a coupled system.

4.2 Software architecture

The coupling framework was implemented in Python because it provides direct access to the FEFLOW IFM API while supporting process control, inter-process communication and runtime data management. Implementing the coupling logic externally avoided modification of either proprietary modelling platform and preserved compatibility with future model updates.

Communication between GoldSim and the Python framework was achieved through a Dynamic Link Library (DLL), which provides the interface required by the GoldSim External Function. Internally, the framework is organised into four independent modules responsible for communication management, groundwater model execution, groundwater flux processing and software interfacing (Figure 2). This modular architecture separates communication, numerical execution and post-processing tasks, reducing dependencies between components and simplifying testing, debugging and future maintenance.

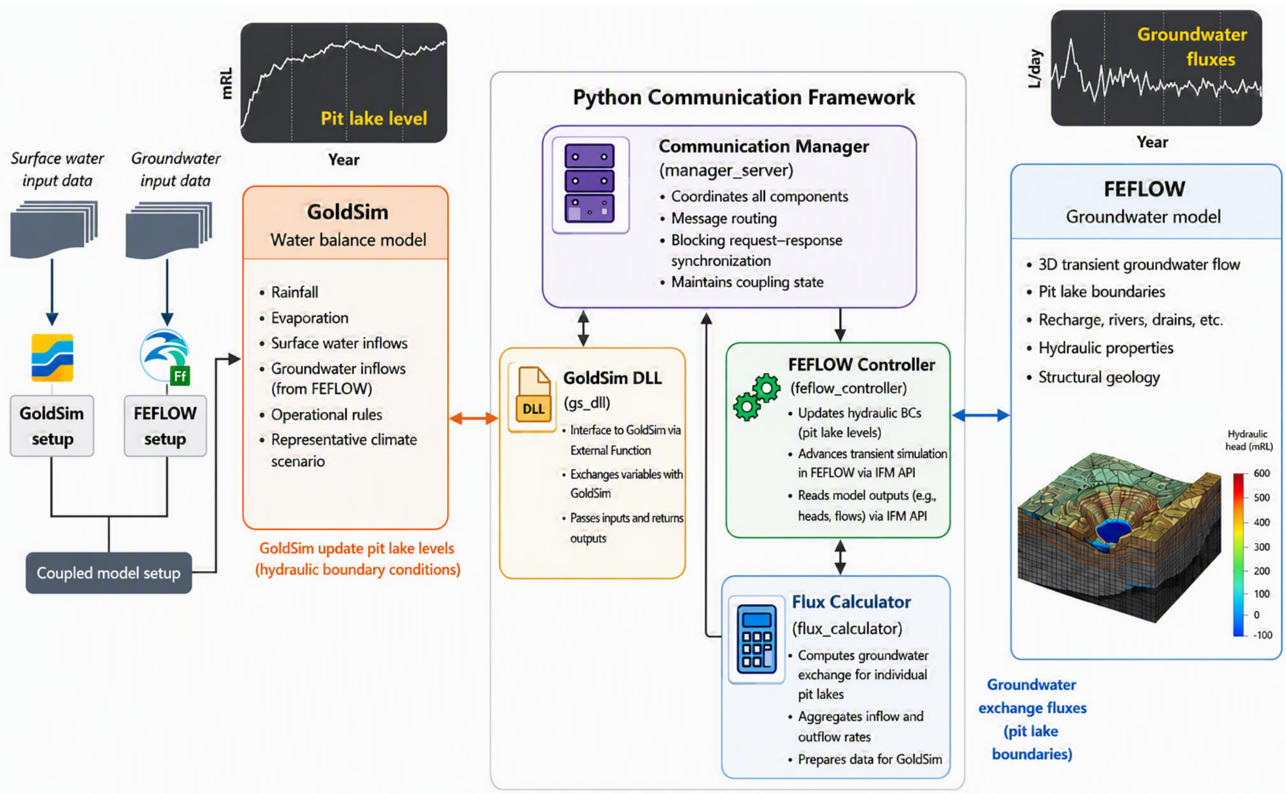

Figure 2 Integrated water balance-groundwater model coupling framework

4.3 Data exchange and synchronisation

GoldSim and FEFLOW execute as independent numerical processes and therefore require explicit synchronisation throughout the coupled simulation. A synchronous request-response protocol was adopted to ensure both models remain at the same simulation time during every coupling interval.

At each synchronisation step, the GoldSim External Function transfers updated pit lake water levels to the coupling framework through the DLL. Execution of the water balance model is suspended while FEFLOW updates the hydraulic boundary conditions, advances the groundwater simulation and computes groundwater exchange fluxes. Once the groundwater simulation is complete, the calculated fluxes are returned to GoldSim, allowing execution to proceed to the next synchronisation interval.

Data exchange is performed directly in memory through a message-passing interface rather than intermediate files. This approach was adopted to minimise communication overhead and eliminate repeated disk input/output operations during the thousands of synchronisation events required for each 300-year predictive simulation.

The synchronisation interval was selected following numerical sensitivity testing. Daily synchronisation resulted in impractical computational times, whereas substantially longer intervals introduced numerical instability because rapid changes in pit lake storage were not propagated to the groundwater boundary conditions with sufficient temporal resolution.

4.4 Timestep and realisations

Different timestep configurations were evaluated to balance simulation stability with practical runtime. GoldSim can efficiently operate at short time steps, however for the three-dimensional FEFLOW model, a one-day time step was not feasible given the computational effort required to simulate 300 years with the probabilistic realisations driven by GoldSim Monte Carlo. Conversely, adopting large groundwater time steps, for example, 60 days, led to instability during coupled exchange. An intermediate configuration was adopted: FEFLOW operated at 15-day time steps, coupled with GoldSim at one-day time steps. This approach achieved stable simulations while keeping runtimes manageable as presented in Figure 3 for a representative pit. Longer groundwater time steps produced oscillations and flux spikes during model coupling (Figure 3a), whereas the adopted 15-day FEFLOW time step reduced these artefacts and improved mass balance consistency (Figure 3b).

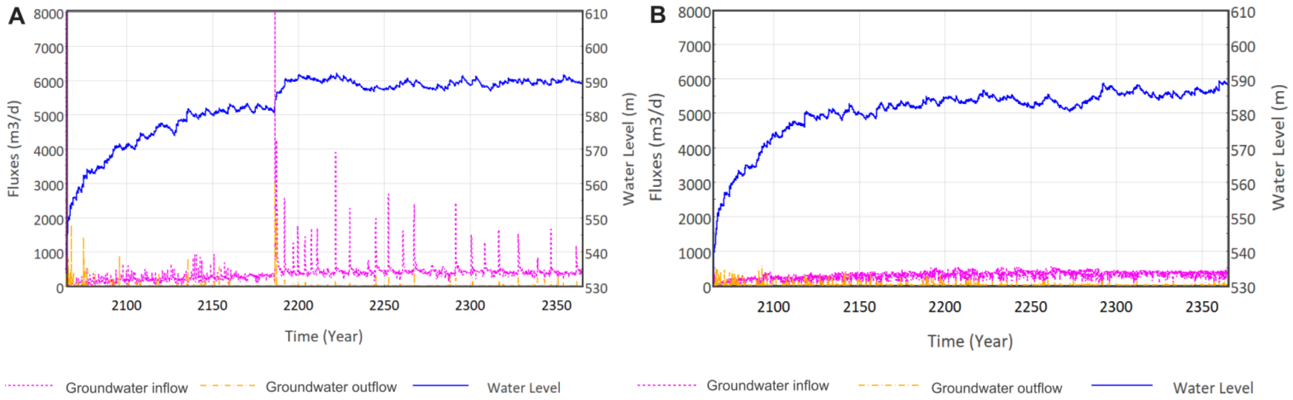

Figure 3 Groundwater inflow instability. (a) 60 day timestep; (b) 15 day timestep

Despite the refinement described above, the computational effort remained substantial and constrained the number of coupled realisations that could be completed within the available timeframe. The Monte Carlo probabilistic analysis capabilities of GoldSim could not be fully utilised within the coupled modelling framework. Therefore, the results should be interpreted as deterministic runs rather than a complete statistical characterisation.

In practice, only three coupled simulations were completed, and the full configuration, 300 years, FEFLOW at 15 days and GoldSim at one day, required slightly more than 50 hours to complete. Three stochastic climate realisations were selected from an ensemble of 100 generated climate sequences. The selected realisations produced total rainfalls of 125,512 mm, 126,492 mm and 127,403 mm over the 300-year simulation period, corresponding to average annual rainfalls of 418 mm, 421 mm and 424 mm, respectively.

While the difference in total rainfall between the selected realisations is relatively small, each realisation includes 300 years of daily variability, incorporating a broad range of wet and dry periods. Consequently, the long simulation period captures diverse hydrological responses, reducing reliance on a large number of additional climate realisations.

The three deterministic realisations approach offered a good variability and similar water level results (average final level around 585 mRL) to those associated with 50 climate stochastic realisations, as presented in Figure 4 for a representative pit, while keeping computational time reasonable. Despite the computational effort and limited number of three realisations, the coupled simulations achieved the decision-support objectives and delivered outcomes required for the project.

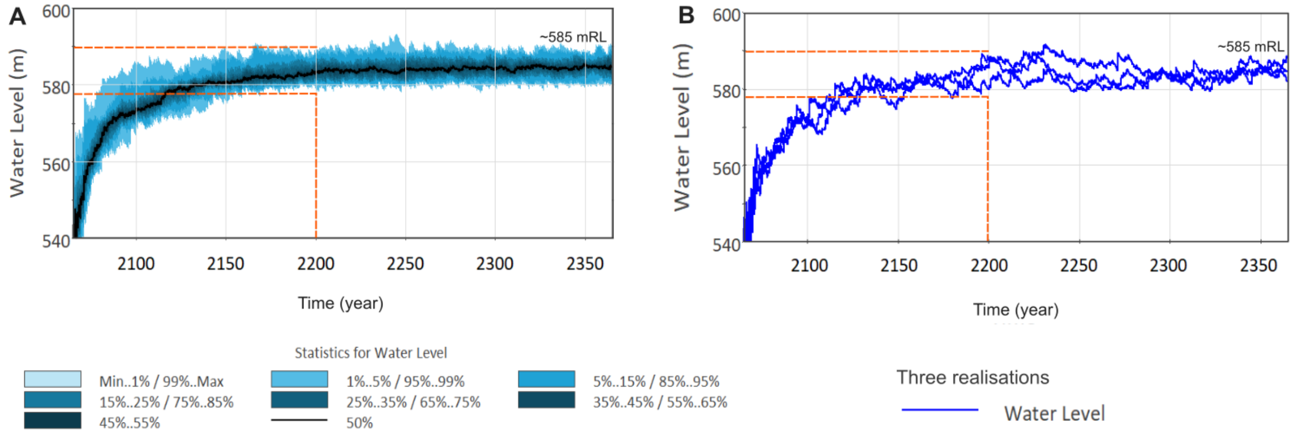

Figure 4 Water level simulation for (a) 50 realisations and (b) 3 realisations

5 Results and discussion

5.1 Inflow and outflows fluxes

Following closure, the modelled pit lakes showed an initially stronger interaction with the surrounding groundwater system reflecting the steep hydraulic gradients established at the end of dewatering. Groundwater inflows were generally higher during the early recovery period and then reduced as pit lake levels rose and hydraulic gradients gradually weakened.

In the base case, groundwater inflows varied between pits because of differences in pit geometry and hydraulic connection. One representative pit, Pit A, showed a gradual increase in inflow during the first approximately 70 years, from about 2,000 m^3/day to 2,800 m^3/day, as the rising lake expanded the lake-aquifer contact area. Once water levels approached more stable conditions, inflows were predicted to remain around 3,100 m^3/day. Another representative pit, Pit B, showed an initial decrease in inflow, from about 6,500 m^3/day, decreasing to approximately 5,000 m^3/day after around 70 years.

In the backfill case, inflows generally declined more rapidly and stabilised at lower rates, reflecting the reduced pit void volume and smaller lake–aquifer contact area. For example, long-term inflows were reported at approximately 2,000 m^3/day for Pit B and generally around 1,500 m^3/day for Pit A. This indicates that backfilling reduced the long-term groundwater exchange between the pit lakes and the surrounding aquifer, although the overall system behaviour remained controlled by the same hydrological processes.

Groundwater outflows were reported to be smaller relative to inflows in both scenarios. In the base case, outflows from the large pit lakes were less than approximately 2% of inflows during the first ~20 years post-closure, equivalent to around 50 m^3/day for both representative pits. As water levels approached equilibrium, outflows progressively declined and tended towards negligible values.

In the backfill case, outflows were slightly higher relative to inflows in the early recovery period, reaching about 20% of inflow in one pit and remaining below 10% in another during the first ~20 years. However, these outflows also declined as recovery progressed, and the systems continued to behave predominantly as terminal sinks over the longer term.

Groundwater inflow and outflow described above for base case and backfill case for the two representative pits are presented in Figure 5.

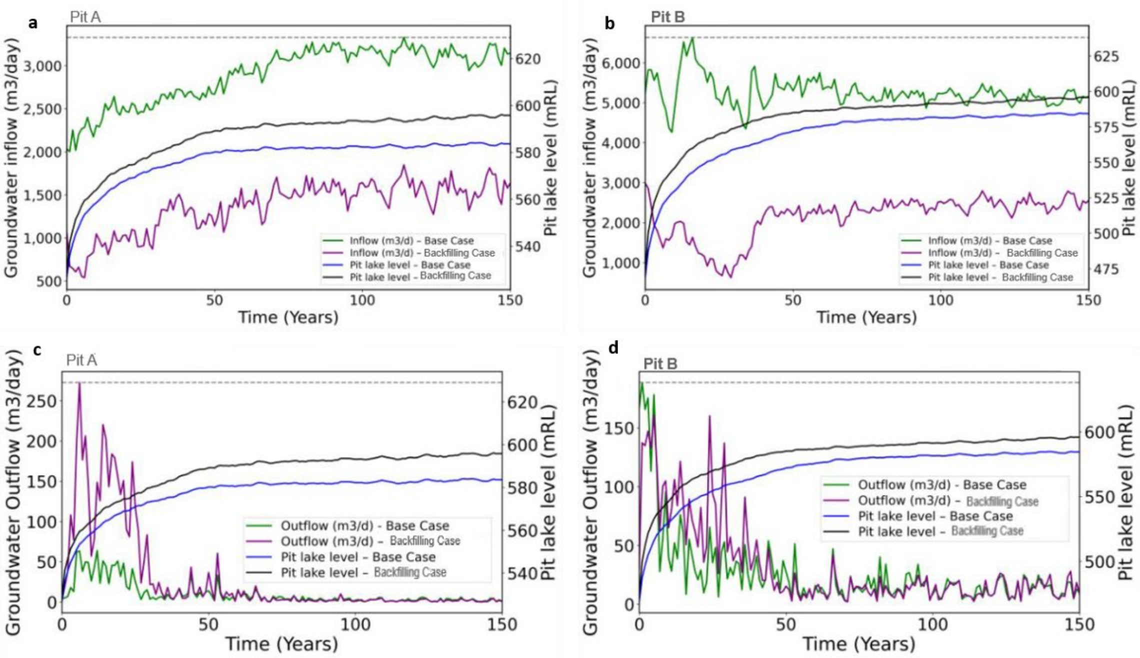

Figure 5 (a) Groundwater inflow for Pit A; (b) Groundwater inflow for Pit B; (c) Groundwater outflow for Pit A; (d) Groundwater outflow for Pit B

The long-term behaviour of all the pit lakes is mainly controlled by the balance between groundwater inflow and evaporation. After approximately 50 years post-closure, groundwater inflow represents roughly 50% of annual evaporative losses. This was observed for both the base case and the backfill case. As a result, evaporation remained the dominant component of the pit lake water balances, limiting the extent of long-term water level recovery. In the backfill case, additional backfilling reduces both lake area and inflow volumes, but these reductions occurred in similar proportion.

5.2 Groundwater and pit lake recovery levels

The post-closure model simulated groundwater level recovery over a 300-year period, commencing from the maximum drawdown condition in Year 0. Groundwater recovery was greatest during the first 50 years following cessation of dewatering, with recovery rates decreasing thereafter for both the base and backfill cases. Groundwater levels continued to recover gradually over the remainder of the simulation period. This pattern reflects the relatively small pit volume within the deeper portions of the system combined with steeper hydraulic gradients during the early stages of recovery, which facilitates more rapid groundwater inflow and redistribution of groundwater flows toward the pits.

For the base case, groundwater recovery at the representative monitoring locations reached approximately 25-32% of total recovery after 10 years, increasing to approximately 51% after 50 years and to approximately 53-59% under long-term conditions (>150 years after closure). Pit lake recovery times varied according to pit type, ranging from 0-50 years for recharge lakes, 34–44 years for through-flow lakes, and 67–163 years for terminal sink lakes. Long-term pit lake depths ranged from approximately 9 to 159 m.

For the backfill case, groundwater recovery for the backfilled pit lakes reached approximately 28–30% after 10 years, increasing to approximately 53–55% after 50 years and to approximately 63% under long-term conditions (>150 years after closure). Recovery times for the remaining pit lakes ranged from approximately 109 to 227 years, with all remaining lakes classified as terminal sinks. Long-term pit lake depths ranged from approximately 59 to 159 m. These levels were approximately 3–6 m higher than those predicted for the base case.

The percentage recovery values shown in Figure 6 represent the proportion of groundwater level recovery following dewatering relative to the total drawdown range and are based on observation points located adjacent to the two representative large pits. For most remaining larger pits in the system, groundwater recovery approached stabilisation between 50 and 100 years after closure.

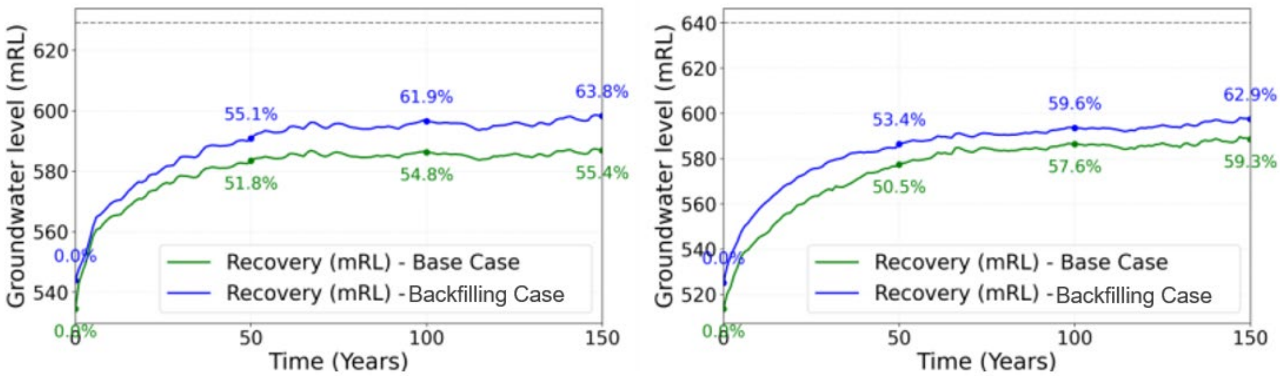

Figure 6 Groundwater recovery for two pits for base case and backfill case

Despite the predicted recovery, groundwater levels do not appear to return to pre-mining conditions within the simulated period. In the base case, groundwater levels stabilised approximately 37–49 m below pre-mining groundwater levels under long-term conditions. In the backfill case, groundwater levels stabilised approximately 29–43 m below pre-mining groundwater levels, indicating a smaller long-term groundwater level deficit than the base case.

The persistence of this groundwater recovery deficit is associated with the long-term pit lake water balance. Model results suggest that evaporation remains a major control on pit lake levels throughout the recovery period, while groundwater inflows stabilise at approximately 50% of annual evaporative losses. As pit lakes recover and their surface areas increase, evaporative losses also increase, which have limited further groundwater and pit lake recovery.

Larger pit lakes generally require longer recovery periods, reflecting the greater water volumes required to fill the remaining void space. In the backfill case, the higher stabilised pit lake levels may be associated with the reduction of the size of the remaining pit voids and, consequently, long-term water losses.

A key finding of this case study is that groundwater levels did not recover to pre-mining conditions within the 300-year simulation period under either closure scenario. Although backfilling reduced the magnitude of the recovery deficit by decreasing pit lake storage, long-term equilibrium remained below baseline groundwater levels. This reflects the dominance of evaporative losses in the long-term pit lake water balance.

5.3 Hydrological behaviour of pit lakes

The model results indicate pit lake behaviour was not static during the recovery period. One representative pit was observed to transition through different hydrological states as hydraulic gradients evolved. These patterns were consistent with the expected bi-directional interactions captured by the coupled framework.

During the early stages of recovery, the pit initially received both direct recharge and through-flow inflow, indicating a complex exchange between the pit lake and the surrounding groundwater system. As groundwater levels continued to recover and gradients flattened, the system gradually shifted towards terminal sink behaviour by approximately 80 to 90 years post-closure. Similar transitions were observed for other pits, reflecting the influence of pit depth, connection to neighbouring voids, and the permeability and structure of the surrounding geological units.

This evolving behaviour is consistent with the modelled recovery trends. The most rapid groundwater and pit lake recovery occurred during the first 50 years after cessation of dewatering, followed by a gradual reduction in in the groundwater level recovery rate. For the larger lakes, water balance stabilisation was generally predicted to occur between approximately 50 and 100 years.

Figure 7a provides a summary of the pit lake-aquifer interactions which were modelled as a time-varying, bi-directional exchanges driven by hydraulic gradients between pit lake levels and simulated groundwater heads. This approach allows for inflow, outflow, or simultaneous through-flow across different parts of the pit. Figure 7b presents a summary of the hydrological behaviour transition during the simulation described above.

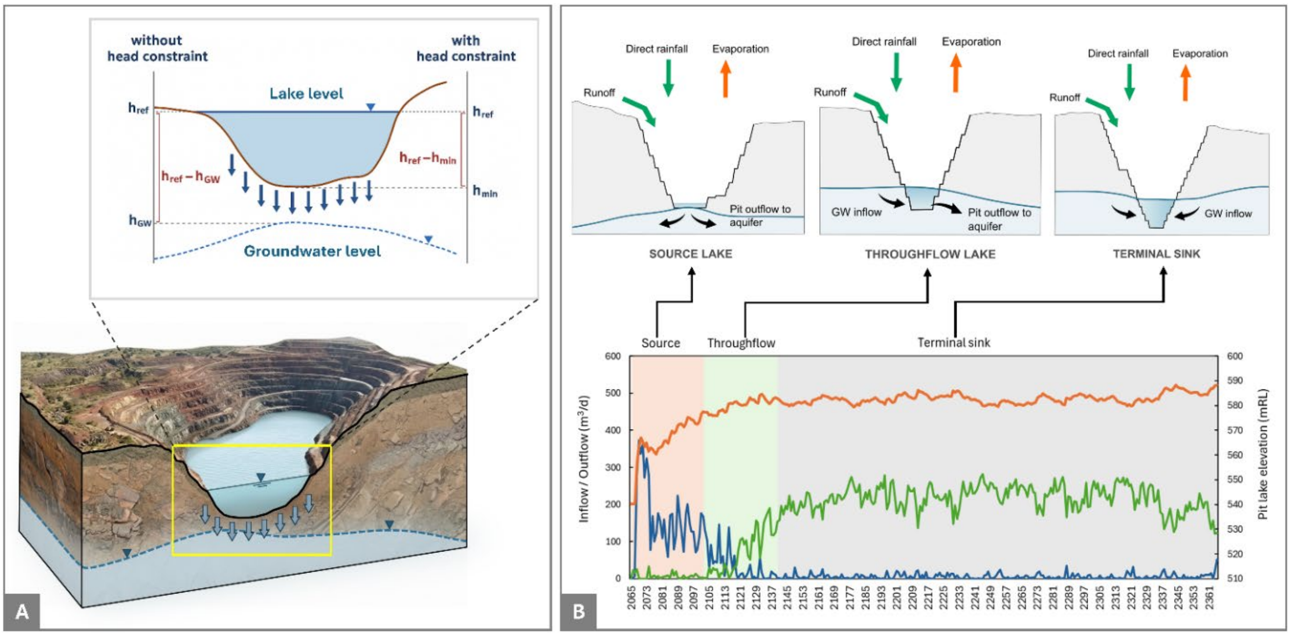

Figure 7 (a) Pit-aquifer interaction - adapted from DHI (n.d.); (b) Hydrological behaviour transition during the simulation

6 Conclusions

This case study showed that long-term pit lake recovery, within the assessed hydraulically connected multi-pit system, was influenced by the interaction between groundwater recovery, pit lake water balances, hydraulic connectivity and structural controls, rather than pit geometry alone. The results indicate that the hydraulic role of a pit lake cannot be inferred from final geometry alone or treated as a fixed classification.

The simulations showed that groundwater exchange and hydraulic connectivity evolve through time as the groundwater system recovers, causing individual pit lakes to transition between sink, through-flow, and source behaviours. For the system assessed, these results indicate that representing pit lake function dynamically can assist in evaluating changes in hydraulic behaviour during closure planning.

Although all pit lakes responded similarly following cessation of dewatering, their hydraulic behaviour diverged as groundwater recovery progressed. Recharge, through-flow and terminal sink lake behaviours emerged through the interaction between groundwater recovery, pit lake water balance and structural compartmentalisation, without predefined classifications. The groundwater level recovery rate was most rapid during the first decades after closure and slowed progressively thereafter. Groundwater levels approached quasi-equilibrium conditions after approximately 50 to 100 years but did not return to pre-mining conditions within the 300-year simulation period because groundwater inflows remained insufficient to offset long-term evaporative losses.

The comparison of closure strategies showed that partial backfilling reduced long-term groundwater recovery deficits and increased stabilised pit lake levels relative to the base case. These results suggest that rehabilitation design may influence post-closure hydrogeological outcomes within the assessed system.

From a methodological perspective, the study showed that independently developed groundwater and pit lake models could be dynamically coupled without modification of either modelling platform. A Python-based communication framework was used to exchange hydraulic information between FEFLOW and GoldSim during runtime. This configuration allowed groundwater–pit lake feedbacks to be represented within a single modelling workflow.

A key limitation of the approach is the substantial computational effort required to maintain dynamic coupling between models. In this large-scale application, simulation runtimes constrained the number of realisations that could be completed and therefore limited the extent of probabilistic analysis that could be practically undertaken.

Despite this limitation, the coupled simulations provided a framework for representing time-varying groundwater-surface water feedbacks, evolving hydraulic connectivity, and interactions between multiple pit lakes. The case study illustrates how a dynamically coupled approach can be applied in a complex multi-pit closure setting where groundwater recovery and pit lake behaviour are strongly interconnected.

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Use of artificial intelligence disclosure statement

In preparing this work, the authors used generative artificial intelligence tools, including Copilot and ChatGPT, to review language and improve clarity and structure. The authors reviewed and edited all generated content as required and take full responsibility for the final manuscript.

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